COMPUTER STUDIES OF AIRCRAFT FUEL TANK RESPONSE TO BALLISTIC PENETRATORS

Richard Alexander Eason

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

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RESPONSE TO BALLISTIC PENETRATORS

by

Richard Alexander Eason

March 1978

Thesis Advisor: R. E. Ball

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A major goal of the hydraulic ram survivability program for aircraft fuel tanks is the development of an economical computer code which accurately predicts the pressure in the fluid, the response of the tank walls, and the crack damage to the tank due to a ballistic projectile. This study compares the tank wall response predicted by the recently modified SATANS code with the

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Computer Studies of Aircraft Fuel Tank Response to Ballistic Penetrators

by

Richard Alexander Eason
Lieutenant, United States Navy
B.S., University of Texas at El Paso, 1969

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ABSTRACT

A major goal of the hydraulic ram survivability program for aircraft fuel tanks is the development of an economical computer code which accurately predicts the pressure in the fluid, the response of the tank walls, and the crack damage to the tank due to a ballistic projectile. This study compares the tank wall response predicted by the recently modified SATANS code with the data from studies performed by California Research and Technology, Inc., the Naval Weapons Center, and the University of Dayton Research Institute. Good agreement among the results is obtained for this phase of the study. Additionally, a comparison of the predicted crack length in the entry wall of the tank using Fahrenkrog's criterion and SATANS' predicted circumferential stresses is made with actual crack lengths from a test performed by the University of Dayton Research Institute. The predicted crack lengths were in excellent agreement with the actual crack lengths.

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I. INTRODUCTION

Fuel tanks in combat aircraft are probably the most vulnerable system in the aircraft. When a bullet or missile fragment penetrates the wall of a fuel tank and enters into the fuel, an intense pressure field propagates throughout the fuel and impinges on the walls of the tank. This is called the hydraulic, or hydrodynamic, ram phenomenon. It is a complicated process, and a considerable amount of research effort has been devoted to it by many investigators in their efforts not only to gain an understanding of the phenomenon but also to develop an economical computer program which accurately predicts the pressure in the fluid and the response of the tank walls. Many of the previous studies were presented at the Hydrodynamic Ram Seminar held at the University of Dayton, Ohio, October 1976. A summary of the hydraulic ram research performed at the Naval Postgraduate School is contained in the symposium proceedings, Ref. 1, and also in Refs. 2 and 3.

The computer studies of hydraulic ram conducted at the Naval Postgraduate School have utilized a computer code called SATANS. A description of the code and subroutines is contained in the user's manual, Ref. 4. SATANS is a structural response digital computer code which has been used to predict the displacements, stresses, and strains in a circular wall of a fluid-containing tank as a function of time. The fluid-structure interaction at the tank wall was accounted for in SATANS by the plane wave piston theory. The piston theory was also

used in the development of the finite element code BR-1HR, which can also be used in fluid-structure interaction problems. However, recent studies have shown that the piston theory assumption that the transverse pressure variations in the fluid can be neglected leads to extremely inaccurate wall response predictions except at very early times, Ref. 5. As a consequence, the SATANS code has been modified to incorporate a more accurate representation of the fluid and its interaction with the motion of the fuel tank walls. The main elements of this modification are presented in Refs. 5 and 6.

Both the original SATANS code and the modified code do not predict the fluid pressure due to the penetrating projectile. This pressure field can be provided by the Naval Weapons Center (NWC) Hydraulic Ram Program--Version One (HRP-V1), Ref. 7. The incident fluid pressure at the fluid-wall interface obtained from this code is used as input data for the modified SATANS code. For the very-early-time, short-duration shock-phase pressure, the Yurkovitch theory can be used, Ref. 8.

An indepth hydraulic ram-structural response study performed by California Research and Technology, Incorporated (CRT), Ref. 9, has been chosen for a comparison with the results obtained using the modified SATANS and HRP-V1 codes in order to develop confidence in both models. CRT compared their computer solutions with an experimental study performed by the University of Dayton Research Institute (UDRI) for verification of their fluid and tank wall response predictions. The CRT study used a two-phase analysis with water as the fluid

and a thin circular plate for the entry wall. In phase I, the AFTON-2D finite difference code was used to calculate the penetration dynamics of a sphere and to determine the fluid pressure at the tank wall. In phase II, the tank wall elastic-plastic response was calculated using the NONSAP-2D finite element code. The pressure at the wall computed in phase I was used as the loading condition for the finite element analysis. Section II of this thesis presents the results from both studies for the projectile velocity and position in the fluid as a function of time, the wall displacement as a function of time, and the circumferential stress vs. radius from center plate at specific times. A comparison of the crack damage prediction with the CRT results is made in section III using a crack damage prediction model developed at NPS by Fahrenkrog, Ref. 10.

II. COMPUTER STUDIES

A. BACKGROUND

When a fluid-backed plate is subjected to pressure from an external source or from within the fluid, the resulting dynamic response of the plate is signficantly affected by the contained fluid. The pressure incident upon the plate causes it to deflect and the fluid pressure at the fluid-plate interface is dependent upon the plate velocity, which leads to a coupled relationship between the fluid pressure and the plate motion. Ref. 11 contains an extensive review of this interaction theory and of some of the finite element and finite difference computer codes used in the analysis of fluid-structure response.

One procedure that eliminates the coupled process is the plane wave piston theory. Fluid-structure interaction has been analyzed using this theory as early as 1940, Ref. 12. Piston theory acknowledges that the pressure radiated from the plate due to plate motion varies both in the transverse plane and in the direction normal to the plate; however, it ignores the transverse pressure variation in the equation governing the pressure field. Ball and Stronge, Ref. 5, have shown that piston theory applied to a water medium does not provide a sufficiently accurate solution for plate motion except at very early times. Their comparison of plate motion, except based upon piston theory, with both a NASTRAN solution and a modified SATANS solution revealed that the influence of pressure relief

in the transverse direction due to non-planar plate motion was significant and should not be neglected.

As a result of the above study SATANS was modified by Ball to incorporate a more accurate representation of the fluid and its interaction with the containment vessel walls. A subroutine was prepared that computes the fluid pressure throughout a cylindrical volume due to tank wall motion. The approach used was to approximate the equations of motion of the fluid by finite difference equations, Ref. 6 and Fig. 1.

B. ENTRY WALL RESPONSE-A COMPARISON WITH CRT RESULTS

To verify the modified SATANS code an indepth study performed by California Research and Technology was chosen for comparison with the SATANS/HRP-V1 results. The problem considered by CRT is shown in Fig. 2. The CRT study utilized a two-phase analysis. In phase I, the penetration dynamics of an 11.1 mm diameter spherical penetrator and the time history of the fluid pressure at the fluid-structure interface were calculated from an adaptation of the AFTON-2D finite difference code. Pressure relief at the fluid-structure interface was accounted for by mass or inertia modeling of the entry wall. Thus, the fluid response is restricted only by the plate mass, and the effect of the plate elasticity is neglected in this phase. The fluid pressure computation in this phase was carried for 178 μsec. In phase II, the entry wall response was calculated using the NONSAP finite element code. NONSAP is a three-dimensional code that accounts for both material and geometrically nonlinear behavior. The interface fluid

pressure computed in phase I was used as the fluid loading on the entry wall. The wall response was computed for time much larger than the 178 μsec. for which the fluid pressure was calculated. For the larger time, the fluid pressure on the wall was neglected. Thus, the plate was essentially vibrating in a vacuum after 178 μsec.

For the computer solutions using SATANS/HRP-V1, the tank dimensions were assumed to be 200 in. x 200 in. x 100 in. deep, with the circular entry panel symmetrically centered on the tank front wall. The dimensions were selected so that during the period of the test runs there would be no reflected images from the other surfaces to interact within the fluid at the plate interface. Input data for HRP-V1 was assembled following the guidelines in the HRP-V1 user's manual, Ref. 7, with the code modified for use on the NPS IBM 360 system.

Ballistic data for the penetrating sphere are presented in Fig. 3. The sphere was assumed to pass directly through an 11.1 mm diameter hole in the entry panel and enters the fluid at coordinates 100,100,0. The HRP-V1 code was used to obtain the entry wall pressures for the first 178 μsec. The fluid interface pressure was not computed beyond 178 μsec in order to make a comparison with the CRT results. Finite difference mesh spacing for the SATANS/HRP-V1 analysis was 0.738 in., and the time step used was 2 μsec.

The displacement and velocity of the spherical projectile calculated as a function of time by the AFTON-2D and HRP-V1 computer codes are presented in Figs. 4a and 4b, respectively.

An examination of these two figures reveals excellent agreement between the results from the two codes. According to Ref. 1 the pressure predicted by these two codes is also in good agreement with the experimental data obtained in the UDRI tests.

Four different computer runs were made for the entry wall response using the SATANS/HRP-V1 codes. Two of the runs considered a linear structural response; one run had the fluid-structure interface pressure relief due to wall motion accounted for, and the other run did not consider the pressure relief. The remaining two runs considered geometrically non-linear structural response, again, one with fluid-structure interface pressure relief accounted for, and one without. All four runs assumed no applied pressure beyond 178 μsec. Figure 5a contains entry displacement at 200 μsec. vs. distance from the impact point obtained from the four SATANS runs and from the CRT study. Figures 5b through 5j present the SATANS geometrically non-linear wall response, with interface pressure relief accounted for, at 200 μsec time intervals up to 2000 μsec. The corresponding data from the CRT study are also presented in these figures.

Examination of Fig. 5a reveals that the effects of geometric non-linearity are small compared to the neglect of interface pressure relief, and that the SATANS/HRP-V1 results predict smaller displacement than does the CRT procedure. However, note that the SATANS/HRP-V1 results do not include the effects of the initial shock pressure due to the initial

penetration predicted by the Yurkovitch theory, Ref. 8. In addition, SATANS results were computed for a plate that did not have an 11.1 mm hole at the plate center, and was linearly elastic. The neglect of the shock pressure probably leads to an underestimation of the entry wall displacement. The presence of the plate where the hole should be accounts for the zero slope at the plate center and probably further restrains the plate motion, as does the linearly elastic restriction.

Examination of Figs. 5b-j reveals that the maximum displacement beyond the hole predicted by the two codes is in very close agreement. Looking at the figures sequentially reveals disagreement, but still a good agreement in relative magnitude.

Figures 6a-d present the circumferential stress vs. distance from the plate center at 50, 100, 150, and 200 μsec for both codes. Examination of these figures reveals that the SATANS data are in excellent agreement with the CRT data in predicting the radial distance beyond which the circumferential stress will be less than the nominal 70 kpsi tensile stress of the 2024-T3 aluminum plate. In addition, the relative magnitudes of the predicted stresses are in good agreement beyond the point at which the stress drops below the 70 kpsi level, however, there is a phasing disagreement similar to that described for Figs. 5b-j. Except for the stress at 50 μsec, the maximum stress predicted by SATANS is higher than that predicted in the CRT study.

C. EXIT WALL RESPONSE-A COMPARISON WITH HRP-V1 MOD RESULTS

The Naval Weapons Center, in the course of studies of the hydraulic ram phenomenon, developed a modification to their hydraulic ram pressure prediction code, HRP-V1, that computes the response of a square exit plate to the pressure predicted by HRP-V1. This modified code, known as HRP-V1 MOD, is extremely quick in execution when compared to the considerably more complex codes like SATANS or BR-1HR.

The original pressure code was modified to include computation of the exit wall response by incorporation of the subroutine VMIRROR. This subroutine provides a variable mirror-image response about the exit wall based on a pressure forcing function that allows incorporation of the pressure interactions into the description of the wall deflection. The specific response model used replaces the free-surface mirror image for the exit wall used in HRP-V1 with an infinite void. A pressure distribution and a fluid velocity are calculated at the exit wall. The structural response of the exit wall is based on the assumption that the plate is simply supported and deflects in a double sine wave form. Both bending and stretching of the middle surface are accounted for. The incident pressure distribution on the plate is calculated from the pressure due to the fluid-projectile interaction. From piston theory, a plane reflected wave is assumed which propagates parallel to the normal to the exit wall. Given initial pressures and fluid velocities at specific time increments, the required pressures and time varying parameters can be calculated and used to predict the exit wall deflections.

The problem selected for comparison with HRP-V1 MOD is shot 14 of the NWC test program, as reported in Ref. 8. The input data for both SATANS and HRP-V1 MOD are given in Ref. 8. The output data from SATANS and HRP-V1 MOD for the deflections at the center of the exit plate as a function of time are presented in Fig. 7. For the time period up to 200 μsec, examination of Fig. 7 reveals that the maximum center plate deflections are in good agreement with a difference of approximately 8%. A plot of the SATANS data for the plate deflection along a radius and the HRP-V1 MOD assumed deflection at 200 μsec is presented in Fig. 8. Relative magnitudes of the deflections compare favorably as does the phasing relationship.

D. CRACK DAMAGE STUDY

A simple procedure for estimating the length of a crack in a fuel tank wall due to hydraulic ram was presented by Fahrenkrog in Ref. 10. Fahrenkrog's procedure is based on several assumptions and observations. First, the fracture surfaces of tank wall plates tested appeared similar to the fracture surfaces on thin plate tensile test specimens, and therefore tensile test data from the stretching of cracked plates can be used. Second, there is a critical stress level for each crack length below which cracks in the tank walls will not propagate.

The CRT case A study and UDRI tests provided data which can be used to substantiate Fahrenkrog's hypothesis about a critical stress level for crack propagation. The calculated circumferential stresses in the entry wall presented in Figs.

6a through 6d reached a maximum close to the plate axis at very early times (less than 200 μsec.) and then decayed rapidly with increasing radius. The stresses above the nominal 70 kpsi tensile stress of 2024-T3 aluminum extend out to a radius of about 4 cm.

The CRT case A corresponds to UDRI test FT5B conditions, Ref. 1. Examination of this test panel revealed that although the test panel contained inelastic distortion, radial cracks did not propagate outward from the entrance hole past about 4 cm.

Figure 9 is a graph which contains Fahrenkrog's plot of stress required for crack propagation versus cracklength from Ref. 10 with results for maximum circumferential stress versus radius from the SATANS analysis at t=200 μsec. Note that the two curves intersect at a point slightly less than 5 cm., and at a stress level of nearly 39 kpsi. Briefly stated, this means that cracks that form around the entry hole should not propagate beyond this length at this time, which is in very good agreement with the UDRI test results.

Fahrenkrog's maximum crack length prediction criterion requires the comparison of the maximum circumferential stress along the radius of the plate with the stress required for crack propagation. A study of the stresses predicted by SATANS for times somewhat larger than 200 μsec revealed that the stress levels dropped, indicating that the crack would not propagate beyond the length shown in Fig. 9. However, for much longer times, i.e, 1 msec $\leq$ t $\leq$ 2 msec, the stress levels

rebounded and peak above those shown in Fig. 9 for radii larger than 4 cm. These maximum stresses are shown in Fig. 10. Hence, a strict application of Fahrenkrog's criterion in Fig. 10 leads to a predicted maximum crack length of 18 cm.

III. CONCLUSIONS AND RECOMMENDATIONS

A. ENTRY WALL RESPONSE

The NWC HRP-V1 computer code is an excellent tool for predicting the fluid pressure field caused by a projectile penetrating a rectangular prism of fluid. When coupled with the current modified SATANS code, the two codes provide a good means of predicting the response of the entry wall of a fluid-filled tank subjected to a penetrating projectile. However, during this study the SATANS code was unable to accurately predict the response of an entry panel when a central hole was introduced to allow projectile entry directly into the fluid.

The modification of the subroutine OUTPUT in the existing SATANS code is an invaluable tool for the analyst because it provides the test plate stresses or strains at discrete radial locations at various times.

B. EXIT WALL RESPONSE

SATANS and HRP-V1 MOD provide close results when predicting the exit wall response at the plate center for early times. Furthermore, the HRP-V1 MOD code uses approximately 1/3 the computer time required by SATANS to predict the response of the exit plate under the same conditions. However, the HRP-V1 MOD code assumes a sinusoidal plate deflection which, when compared to deflections predicted by SATANS, gives a plate displacement that may be too smooth.

At the present time, the HRP-V1 MOD program is limited to predicting only exit wall response. Further study should be

performed with the HRP-V1 MOD code to determine if it can be modified to also predict entry wall response.

C. CRACK DAMAGE STUDY

The SATANS code with the modified OUTPUT subroutine prints stress levels in the entry panel which are in reasonable agreement with the CRT and UDRI test results for stresses below the maximum tensile stress, up to 200 μsec. When the SATANS-predicted circumferential stresses at 200 μsec, versus radius, is applied to Fahrenkrog's crack length prediction criterion, the predicted crack lengths are nearly the same as the lengths actually measured under controlled testing by UDRI test FT5B. When maximum predicted circumferential stress vs. radius is applied to Fahrenkrog's criterion, the maximum predicted crack length is appreciably longer.

Because the SATANS data in conjunction with Fahrenkrog's crack length prediction criterion predicted conservative results compared with the actual test results from UDRI, further comparison should be performed with actual test results from several different tests. These comparisons will help to establish a standard for crack length prediction in fluid-filled tanks subjected to a penetrating projectile.

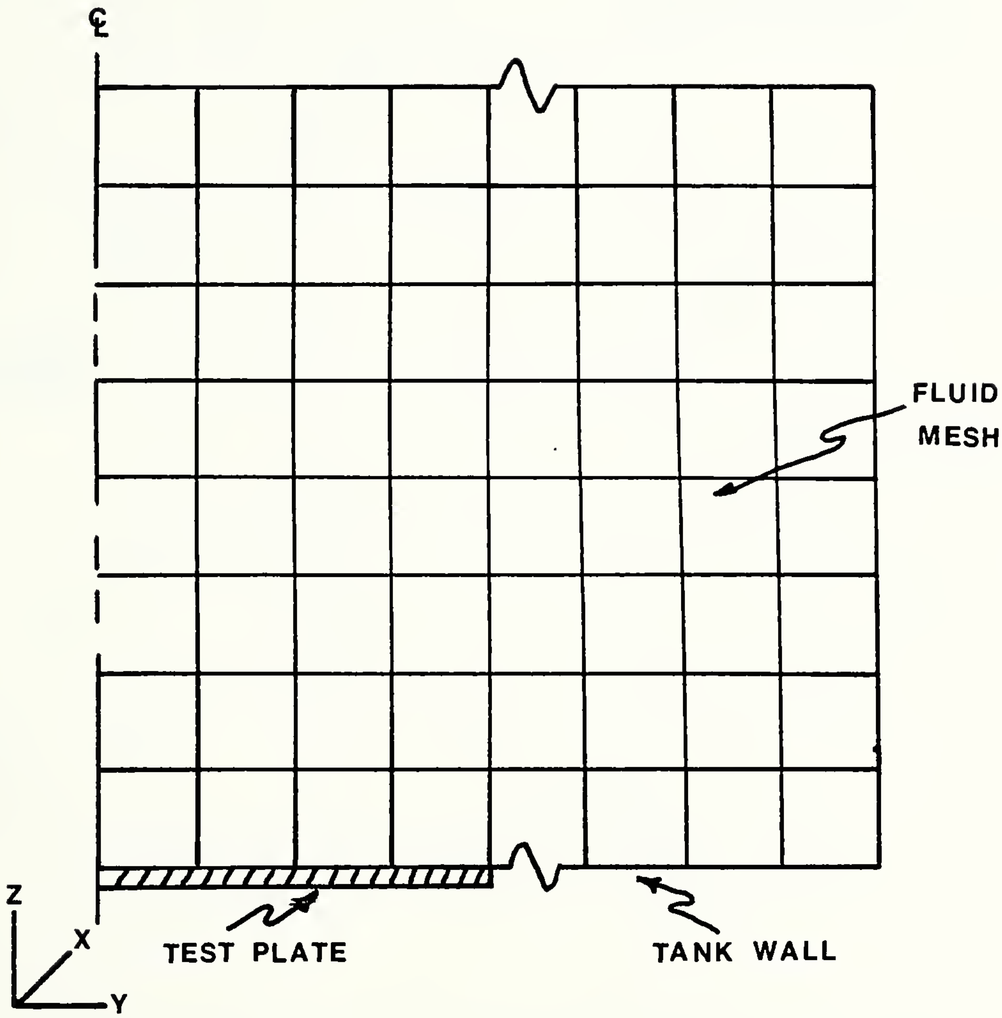
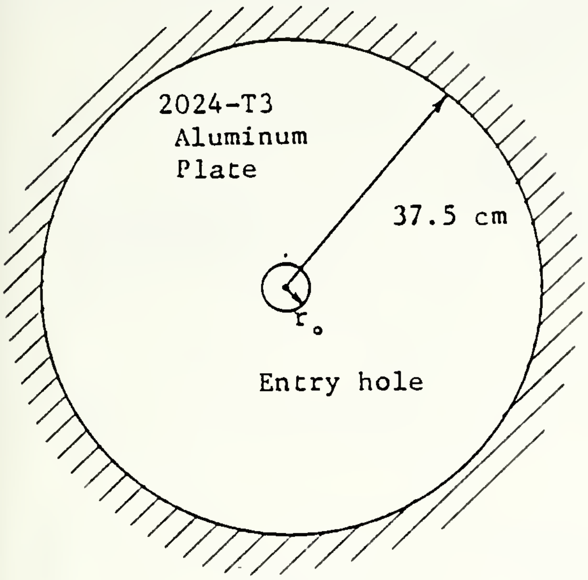
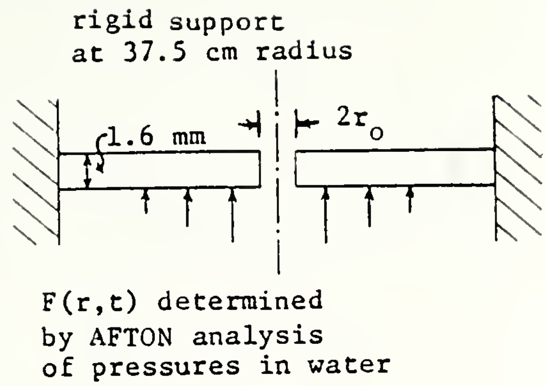


FIGURE 1

ENTRANCE PANEL GEOMETRY:

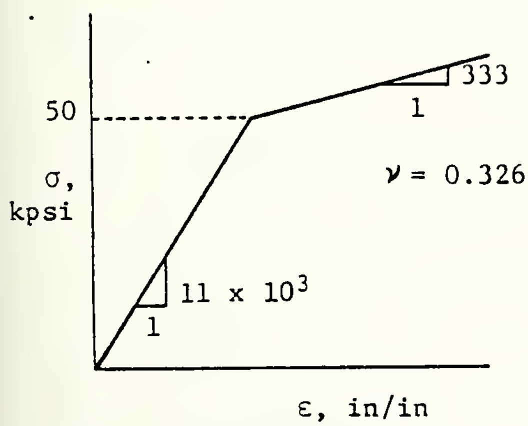


END VIEW



CROSS-SECTIONAL VIEW

2024-T3 ALUMINUM
MATERIAL MODEL:



GRID SIZE:

$2r_o$	No. Elements	No. Nodes
11.1 mm	56	283
14.3 mm	55	278

TIME STEP:

$\Delta t = 2\ \mu sec$

FIGURE 2: NONSAP Finite Element Axisymmetric Model of the Entrance Panel of the Fuel Tank

CONDITIONS FOR CRT CASE A CALCULATIONS

AND EXPERIMENTAL COMPARISONS

IMPACTING SPHERE		
DIAMETER (cm)	MASS (gm)	DRAG COEFFICIENT (C_D)
1.11	5.5	0.6

ENTRANCE PANEL	
2024-T3 AL THICKNESS(cm)	AVCO BALLISTIC FOAM THICKNESS
0.16	0

UDRI TEST	ACTUAL TEST VELOCITY (m/s)	OBSERVATIONS AVAILABLE FOR COMPARISON
FT5B	1550	.time resolved entry panel profiles .damage severity

FIGURE 3

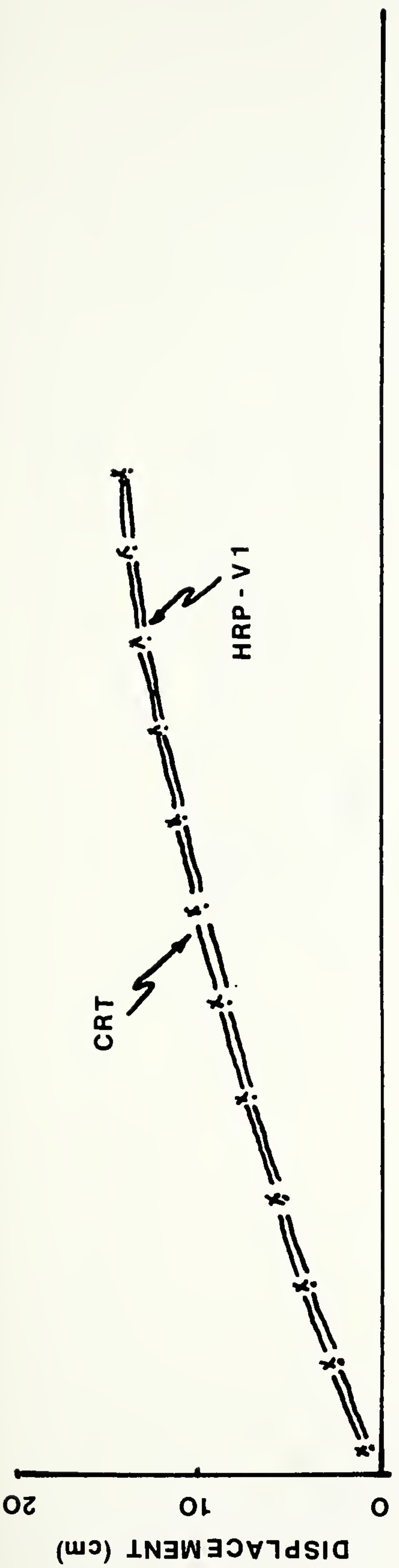


FIGURE 4- A

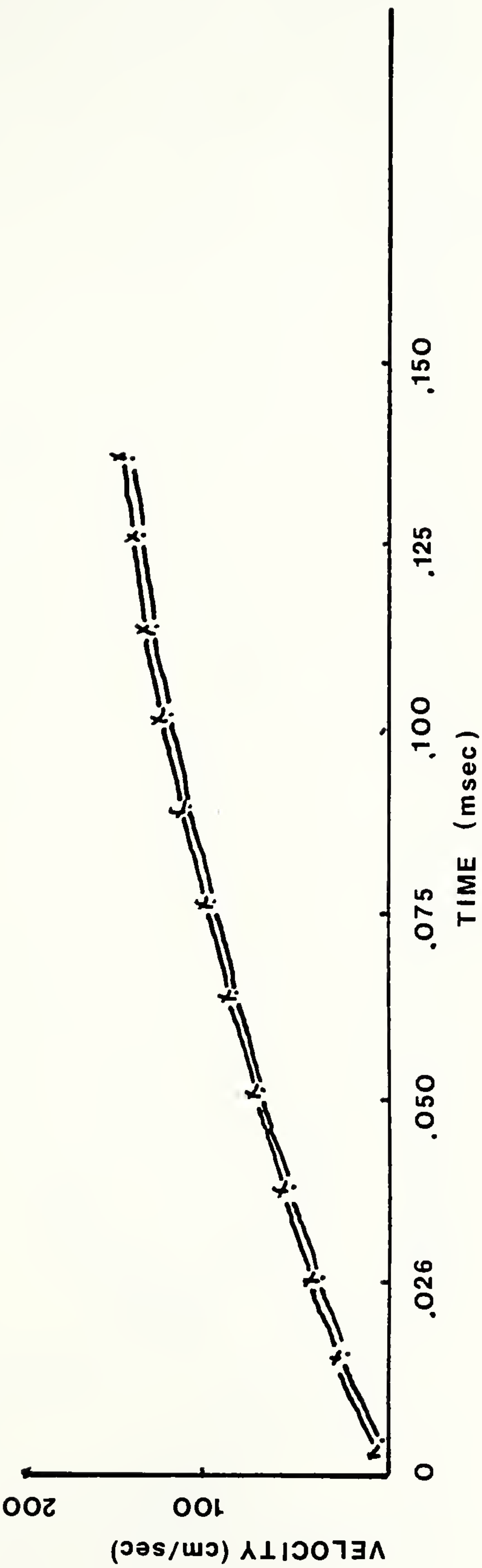


FIGURE 4—B

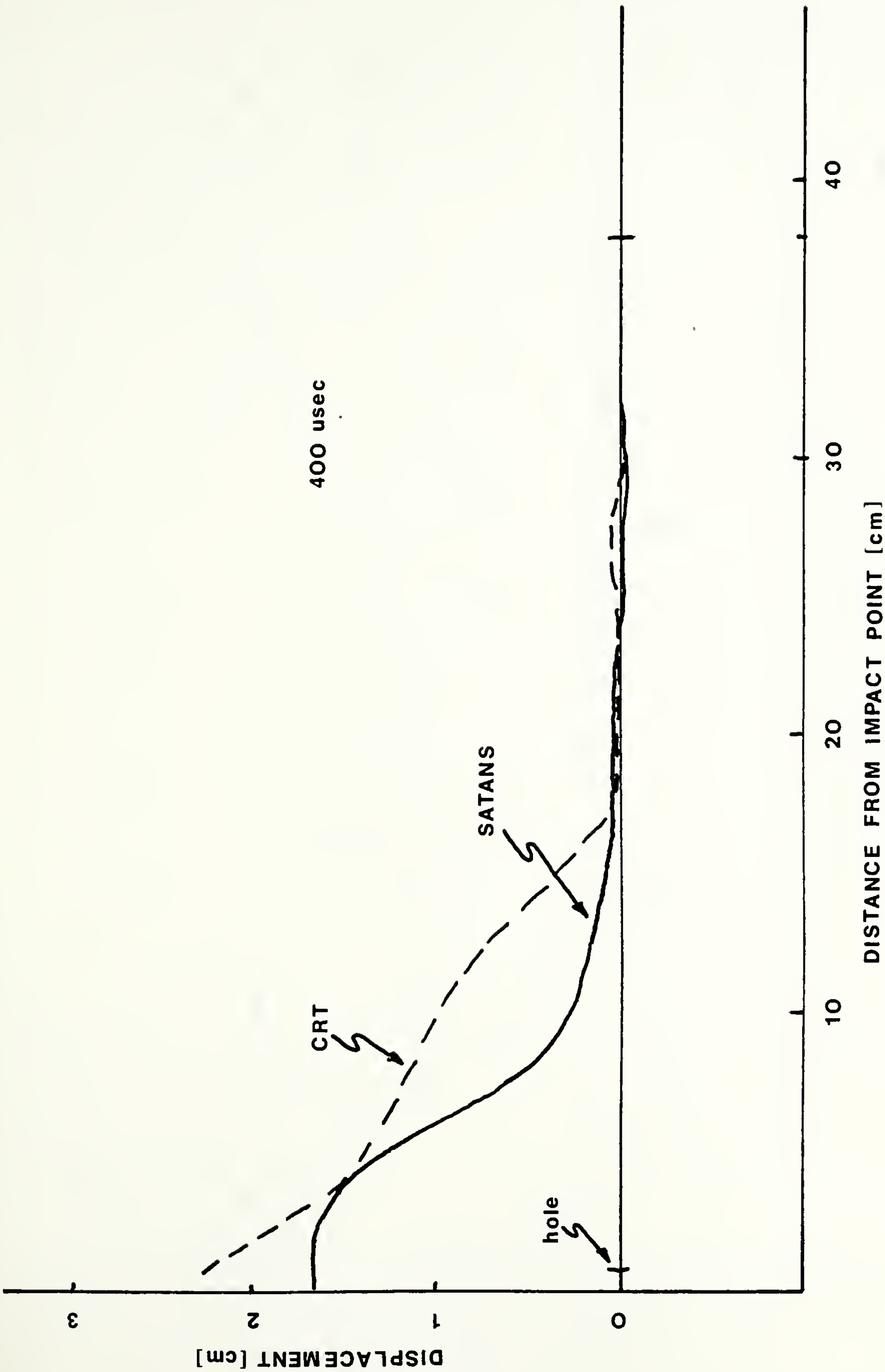

400 usec
CRT
SATANS
hole
DISPLACEMENT [cm]
0
1
2
3
10
20
30
40
DISTANCE FROM IMPACT POINT [cm]

FIGURE 5-B

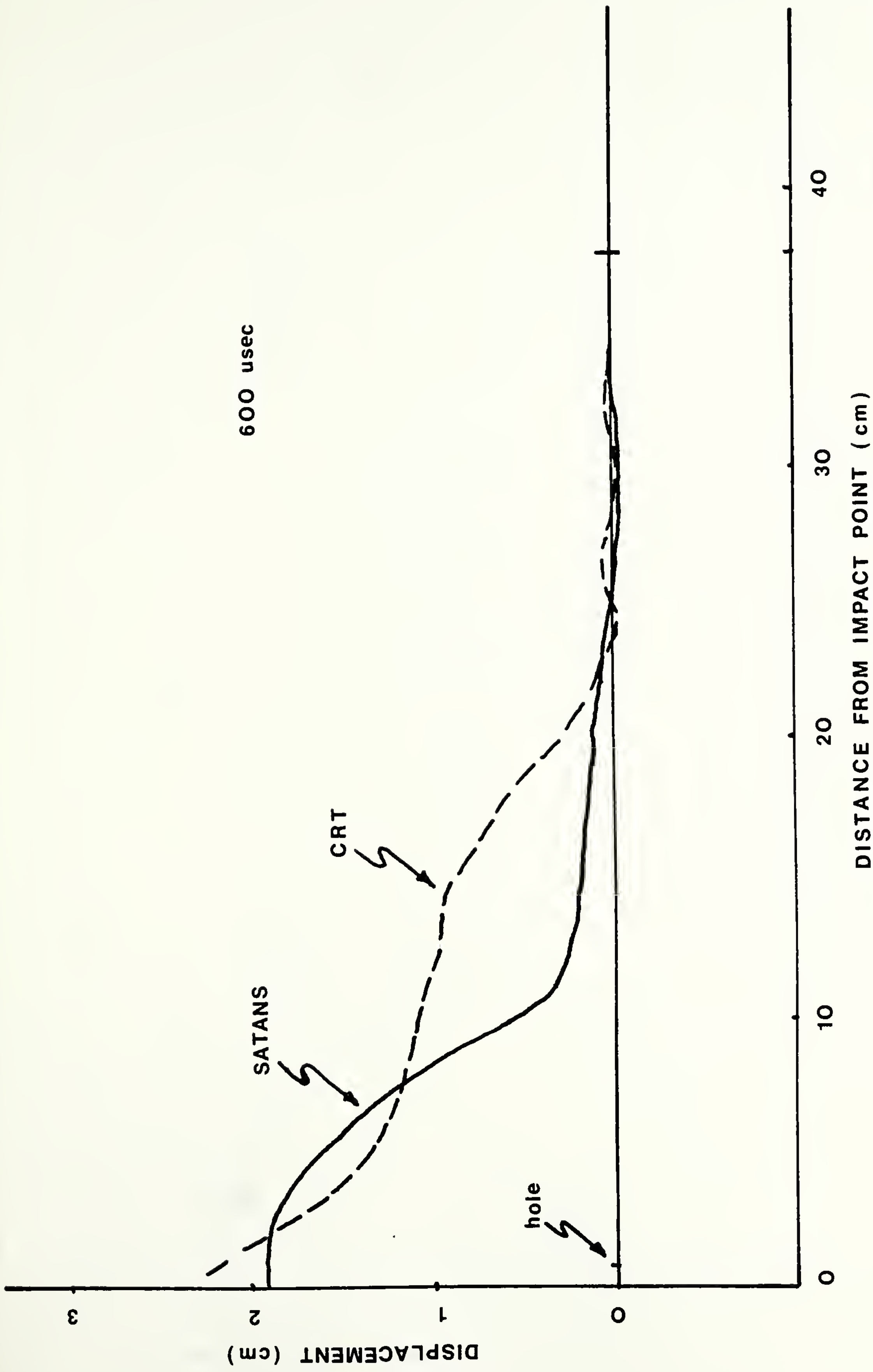

600 usec
SATANS
CRT
hole
DISPLACEMENT (cm)
0
1
2
3
0
10
20
30
40
DISTANCE FROM IMPACT POINT (cm)

FIGURE 5 – C

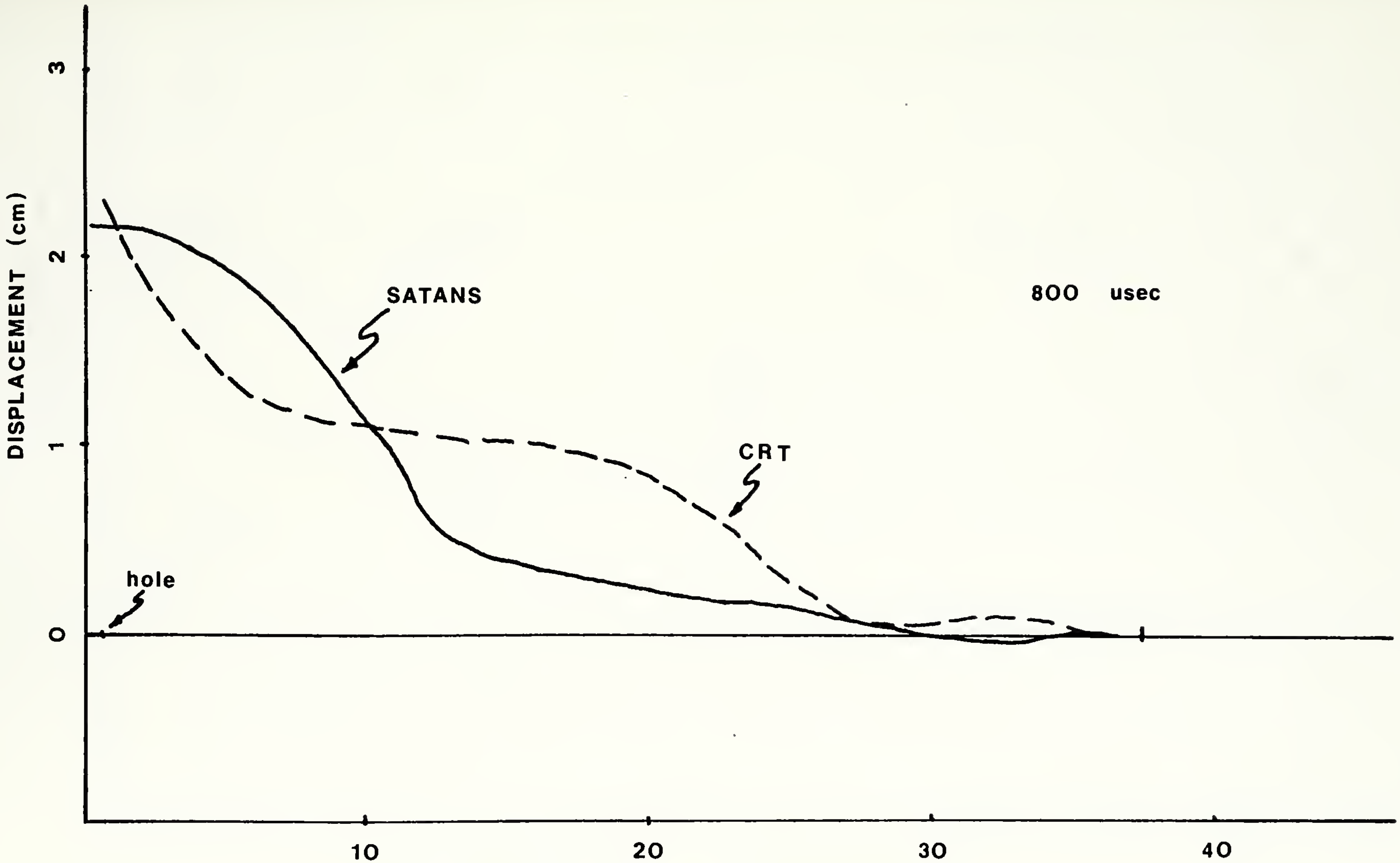

800 usec
SATANS
CRT
hole
DISPLACEMENT (cm)
0
1
2
3
10
20
30
40
DISTANCE FROM IMPACT POINT (cm)

FIGURE 5-D

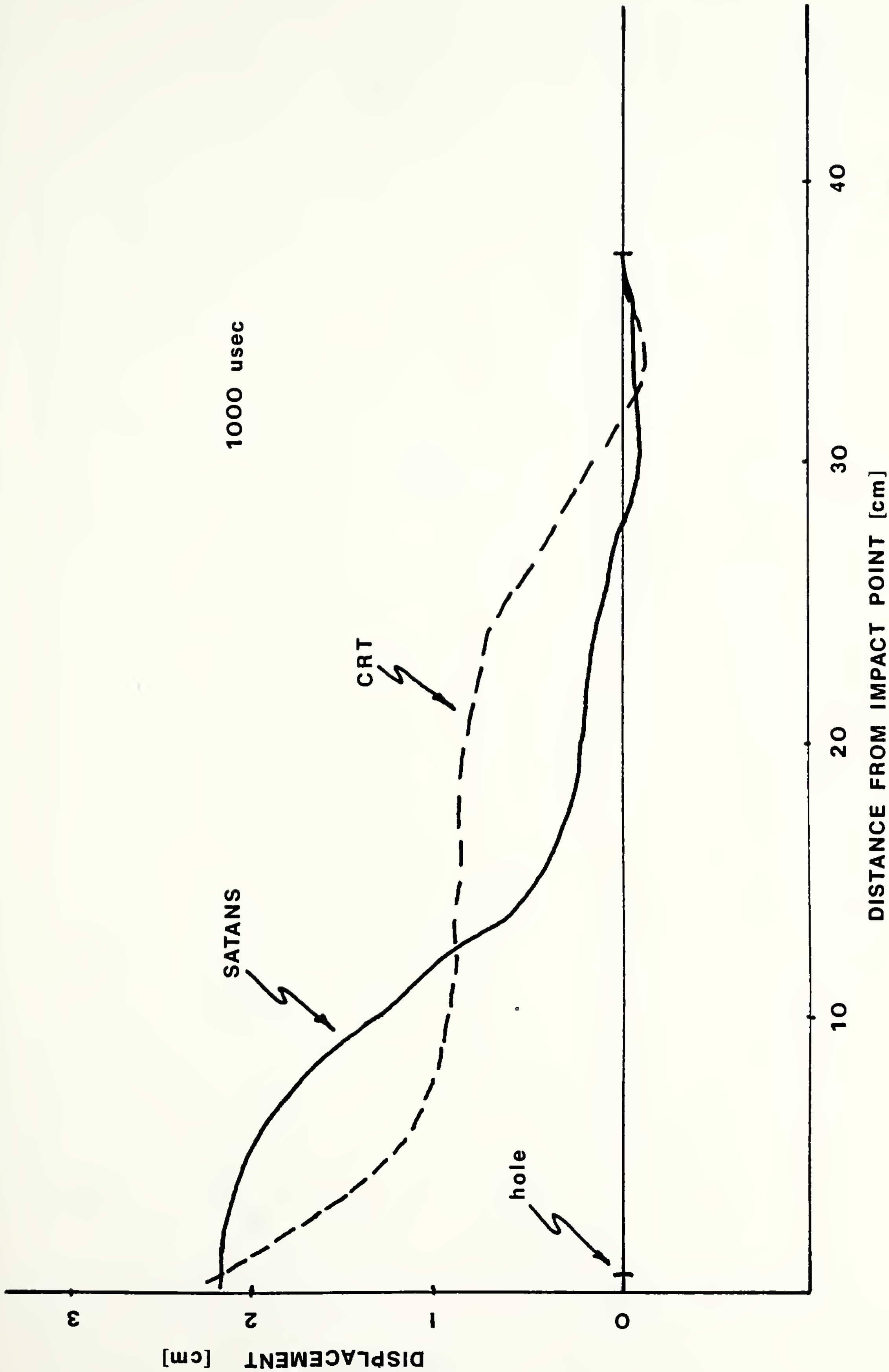
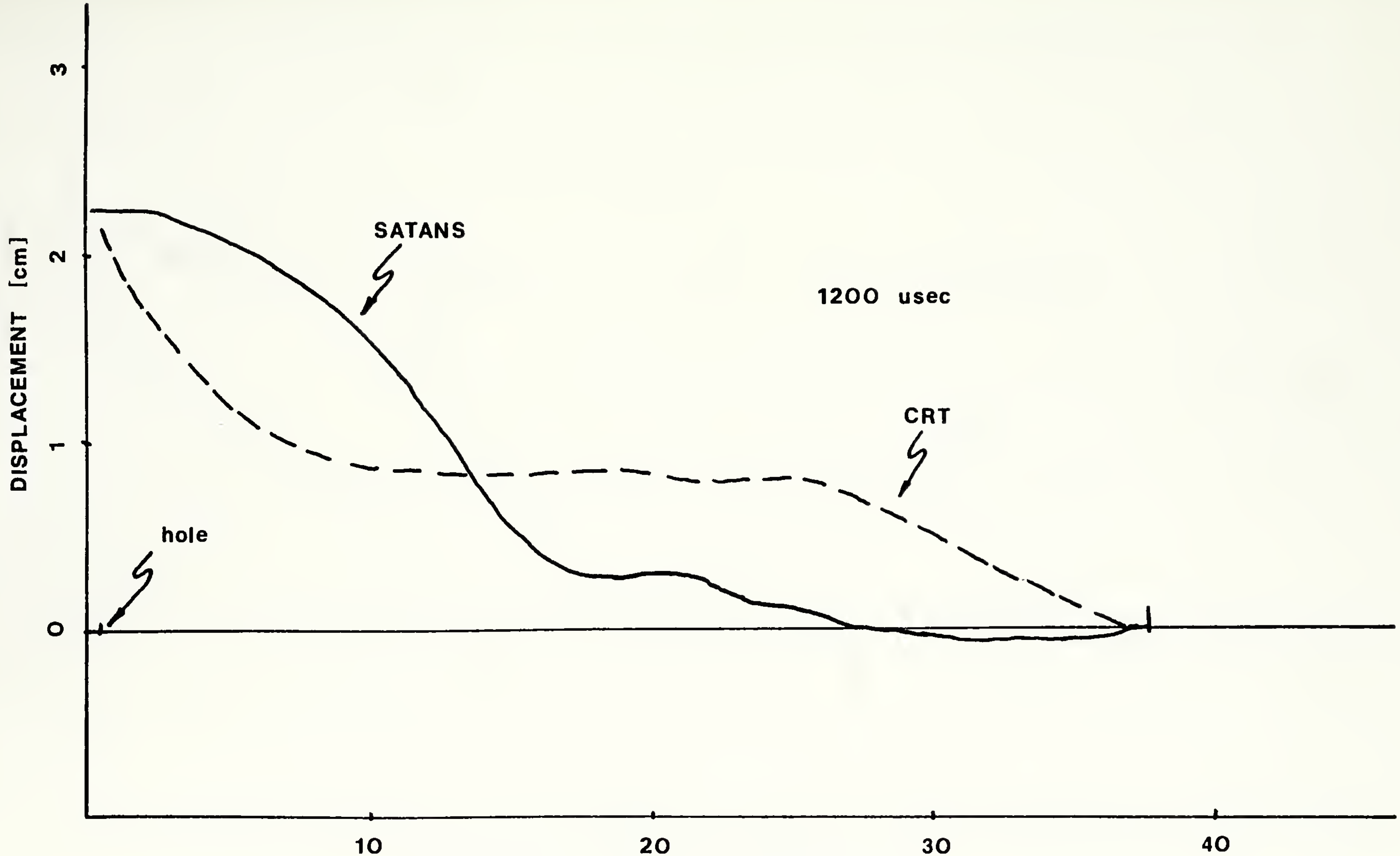

1000 usec
SATANS
CRT
hole
DISPLACEMENT [cm]
0
1
2
3
10
20
30
40
DISTANCE FROM IMPACT POINT [cm]

FIGURE 5-E



1200 usec
SATANS
CRT
hole
DISPLACEMENT [cm]
0
1
2
3
10
20
30
40
DISTANCE FROM IMPACT POINT [cm]

FIGURE 5-F

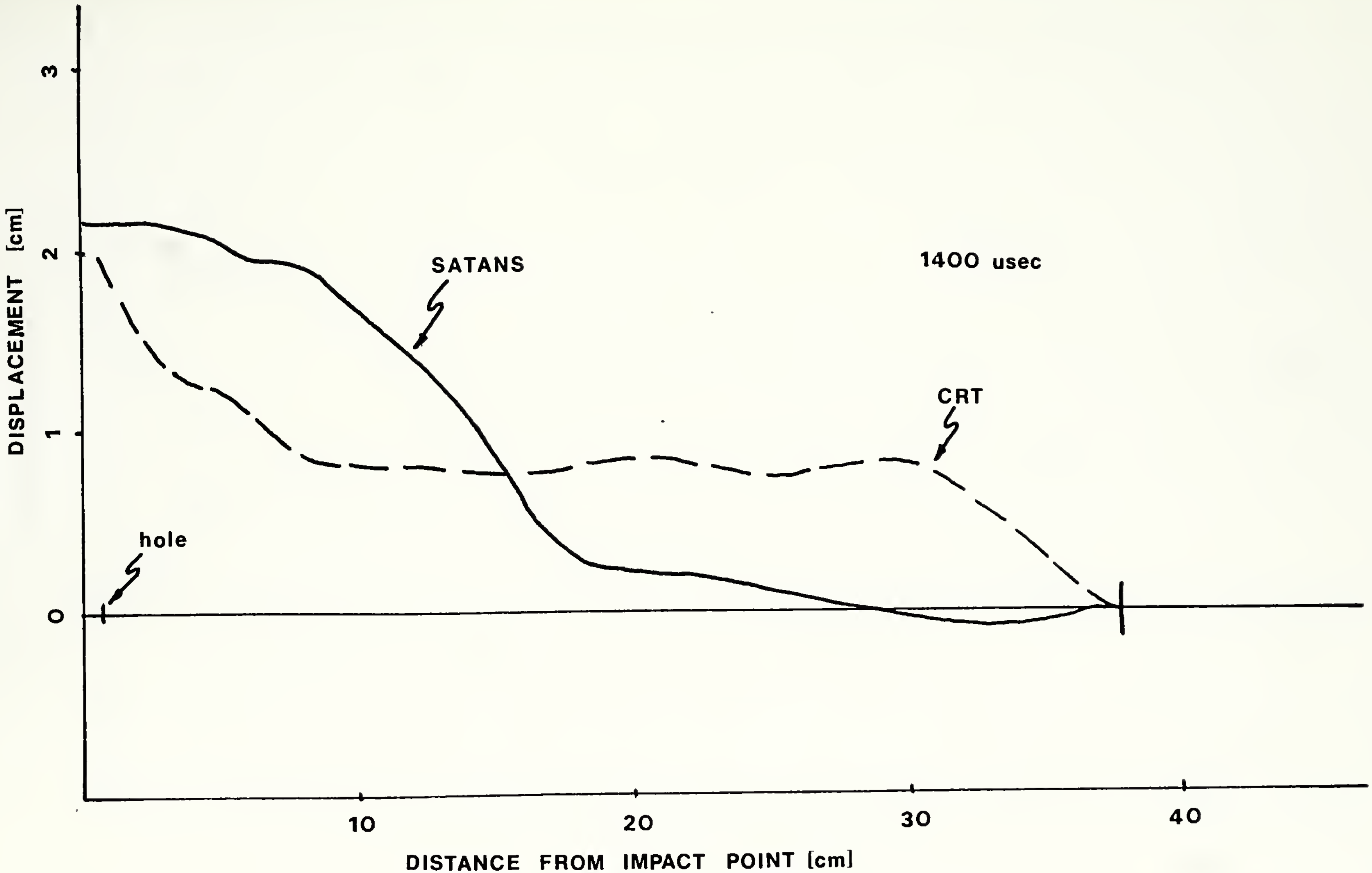

1400 usec
SATANS
CRT
hole
DISPLACEMENT [cm]
0
1
2
3
10
20
30
40
DISTANCE FROM IMPACT POINT [cm]

FIGURE 5 - G

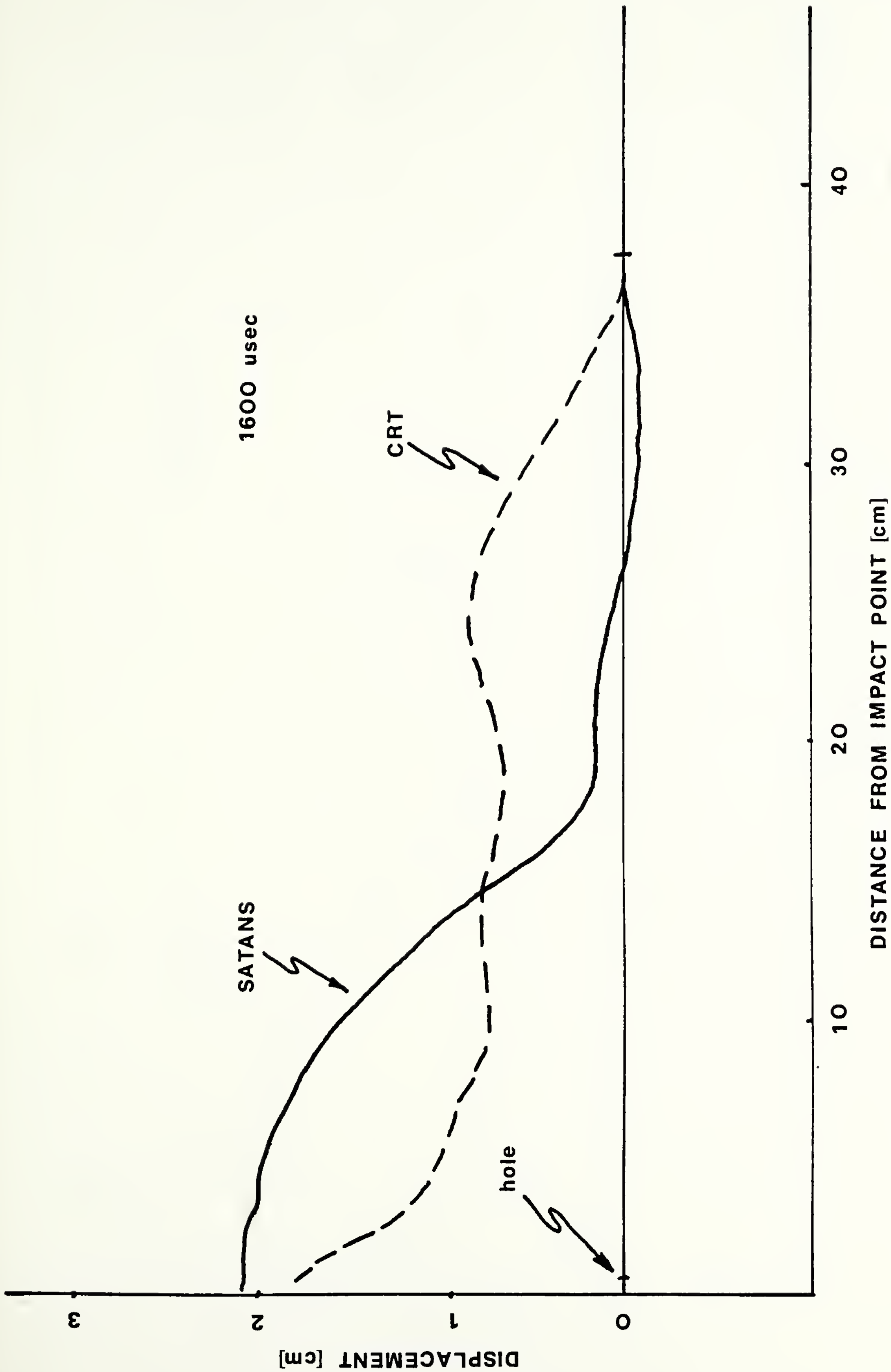
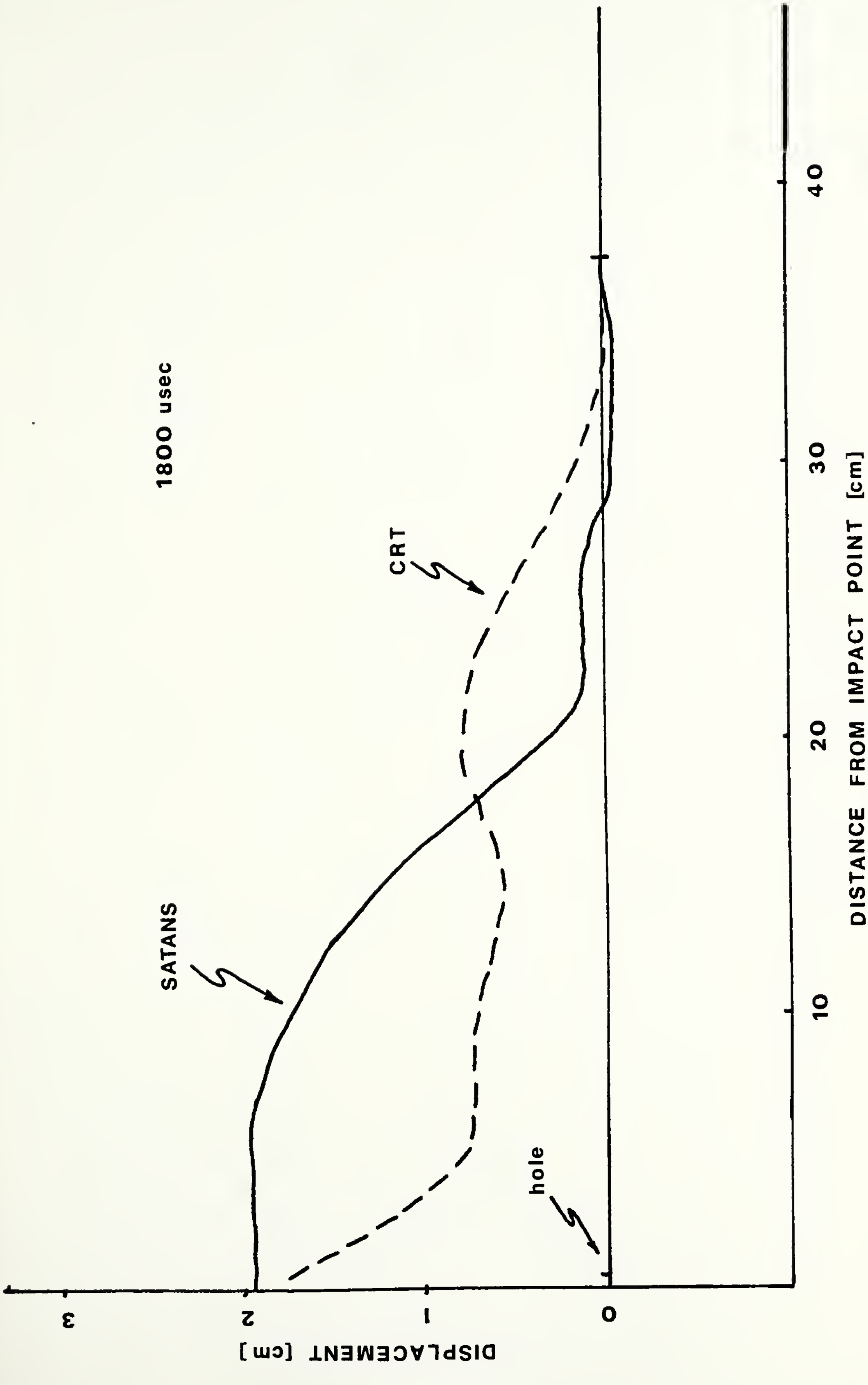

1600 usec
CRT
SATANS
hole
DISPLACEMENT [cm]
0
1
2
3
10
20
30
40
DISTANCE FROM IMPACT POINT [cm]

FIGURE 5 - H



1800 usec
SATANS
CRT
hole
DISPLACEMENT [cm]
0
1
2
3
DISTANCE FROM IMPACT POINT [cm]
10
20
30
40

FIGURE 5 - I

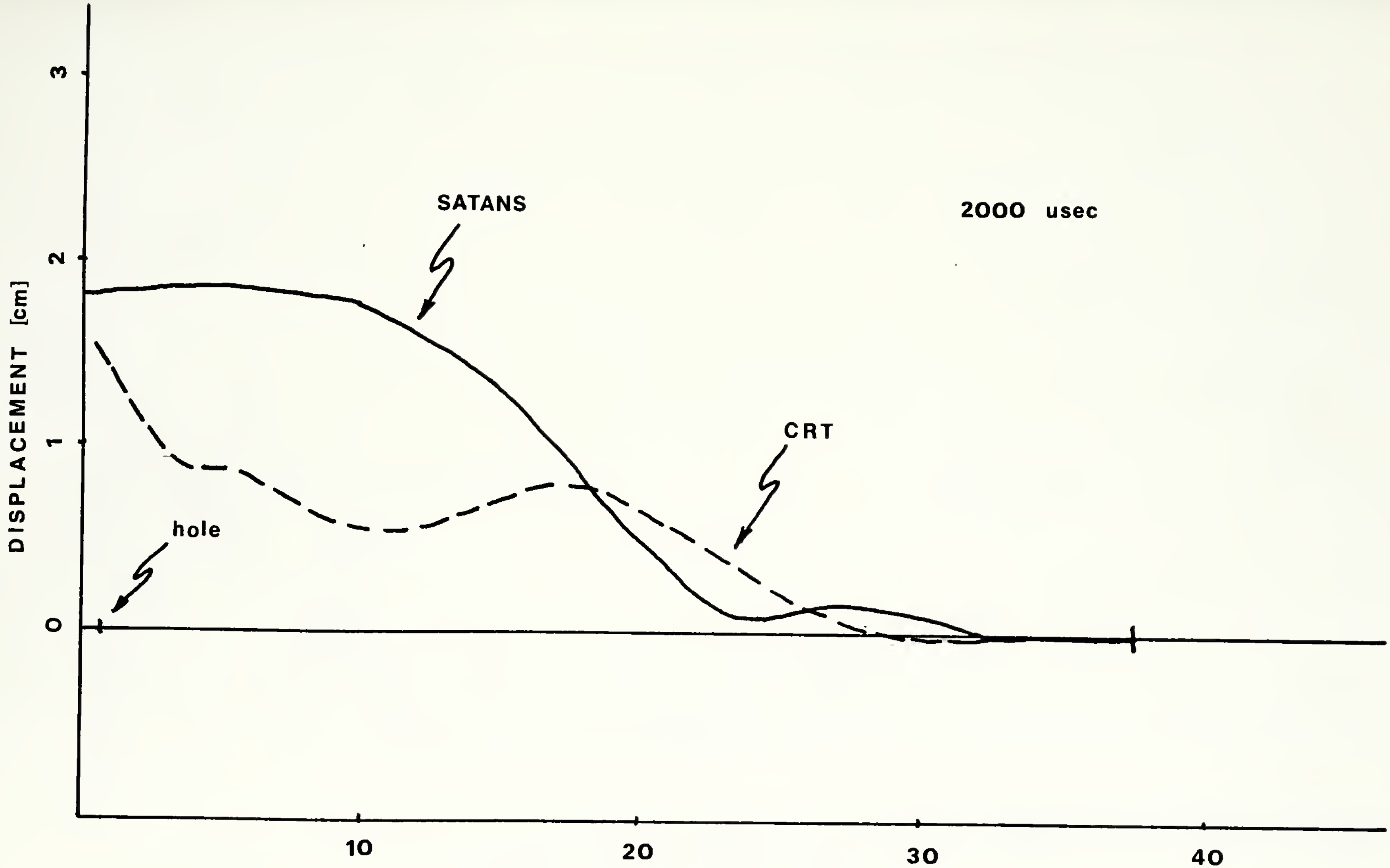
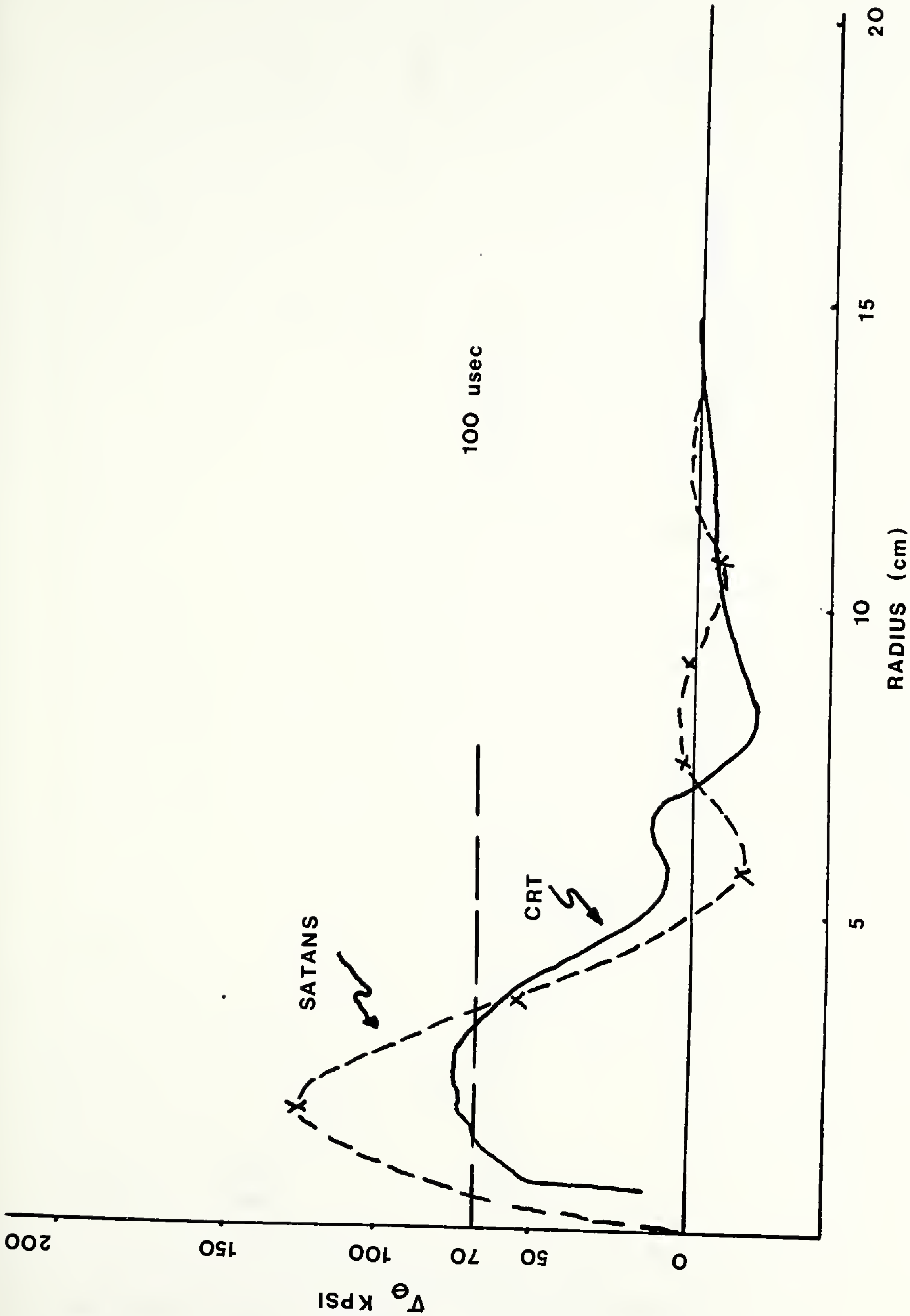

2000 usec
SATANS
CRT
hole
DISPLACEMENT [cm]
0
1
2
3
10
20
30
40
DISTANCE FROM IMPACT POINT [cm]

FIGURE 5-J



200
150
100
70
50
0
σθ KPSI
SATANS
CRT
100 usec
5
10
15
20
RADIUS (cm)

FIGURE 6-B

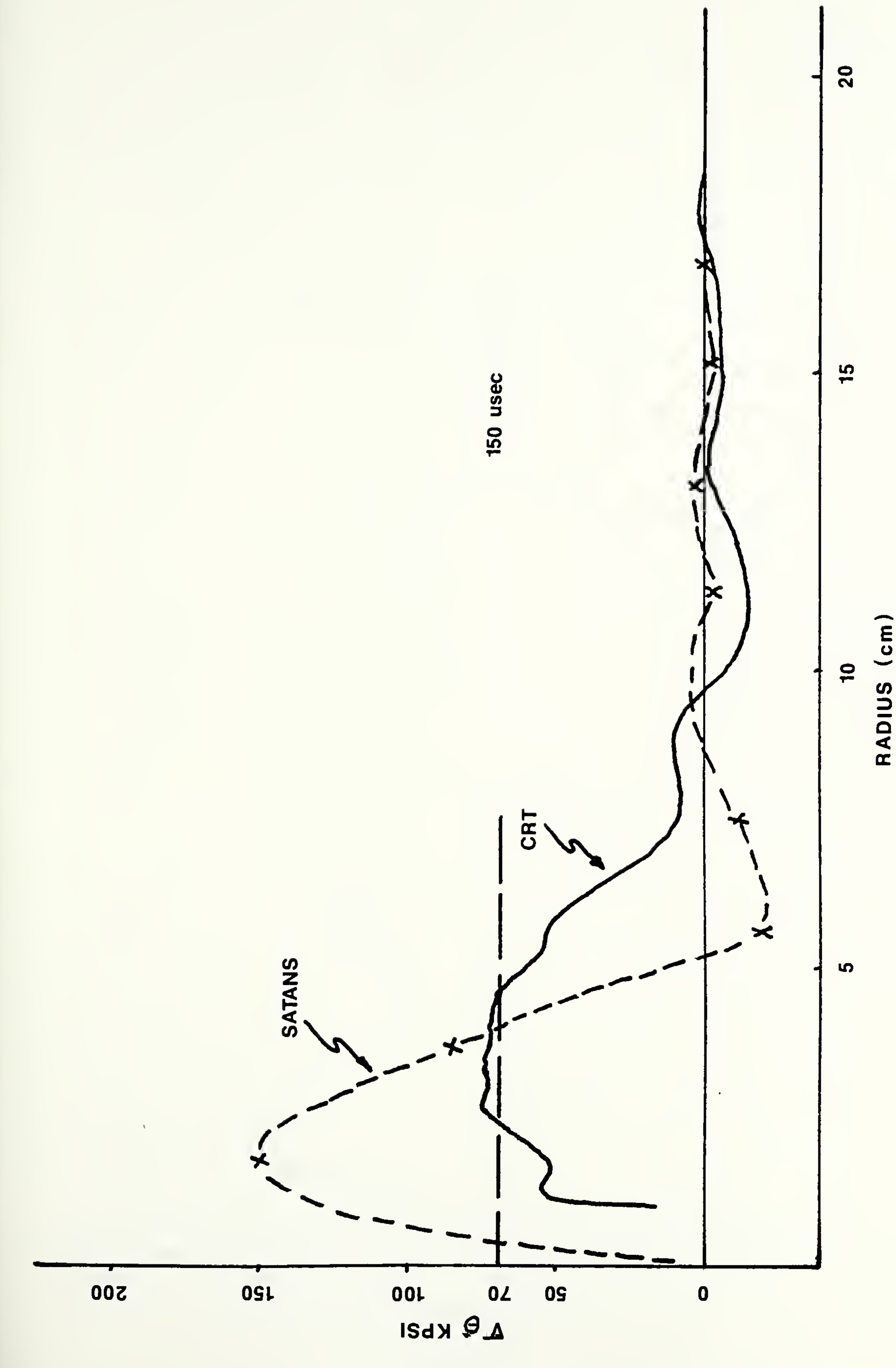

150 usec
SATANS
CRT
σ_θ KPSI
200
150
100
70
50
0
5
10
15
20
RADIUS (cm)

FIGURE 6-C

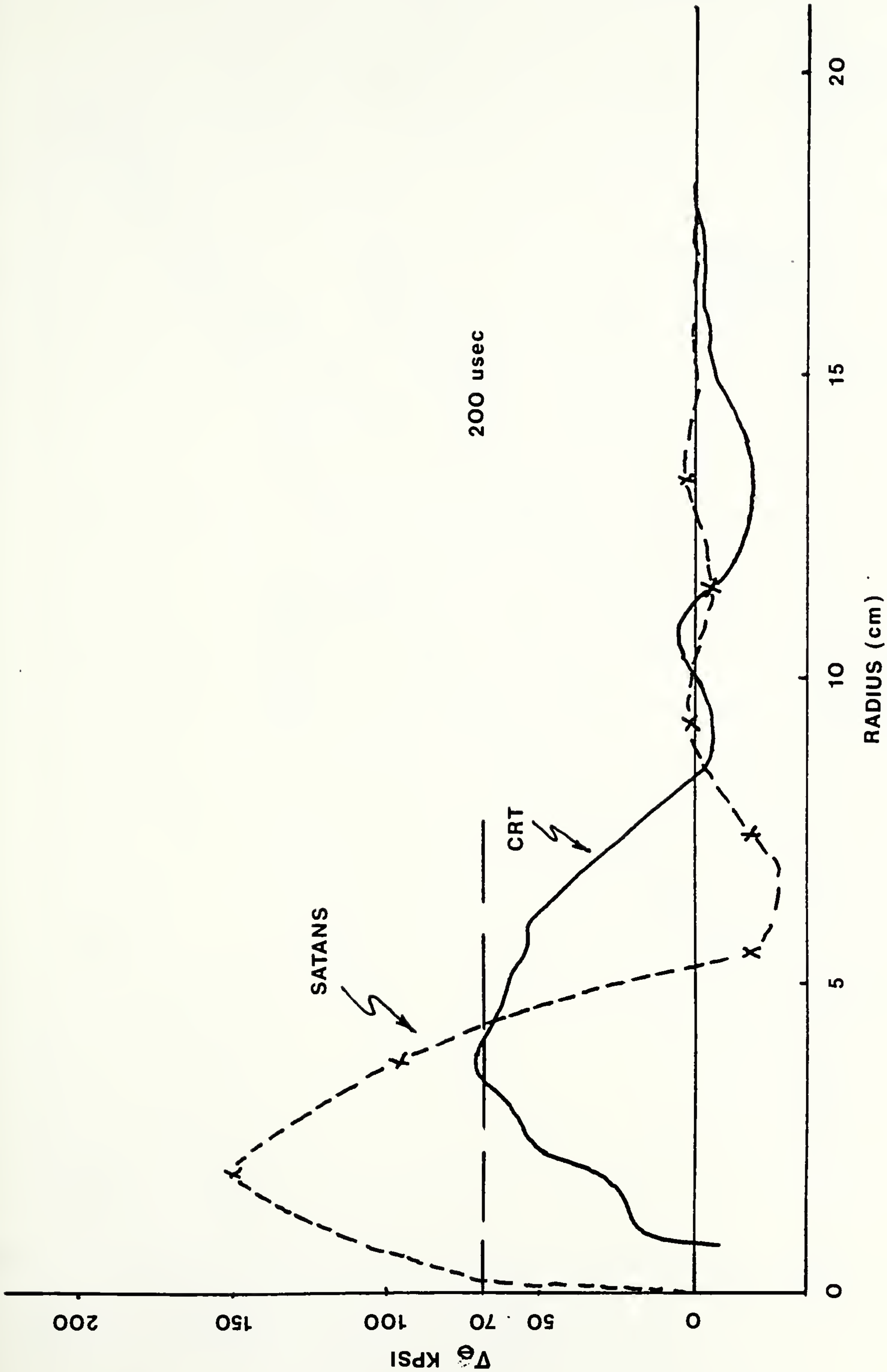

200 usec
SATANS
CRT
0
50
70
100
150
200
V_θ KPSI
0
5
10
15
20
RADIUS (cm)

FIGURE 6-D

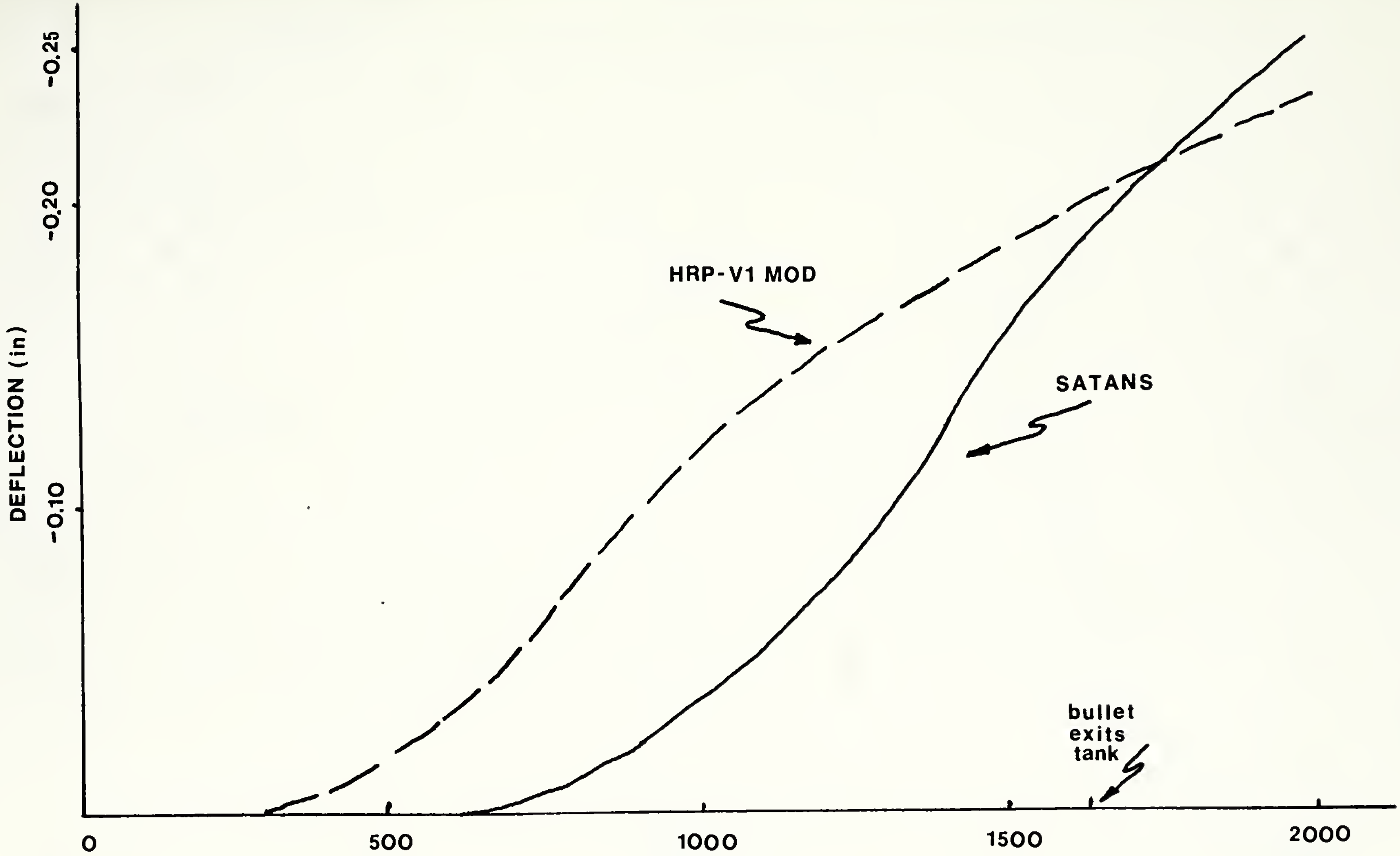

DEFLECTION (in)
-0.25
-0.20
-0.10
HRP-V1 MOD
SATANS
bullet
exits
tank
0
500
1000
1500
2000
TIME (usec)

FIGURE 7

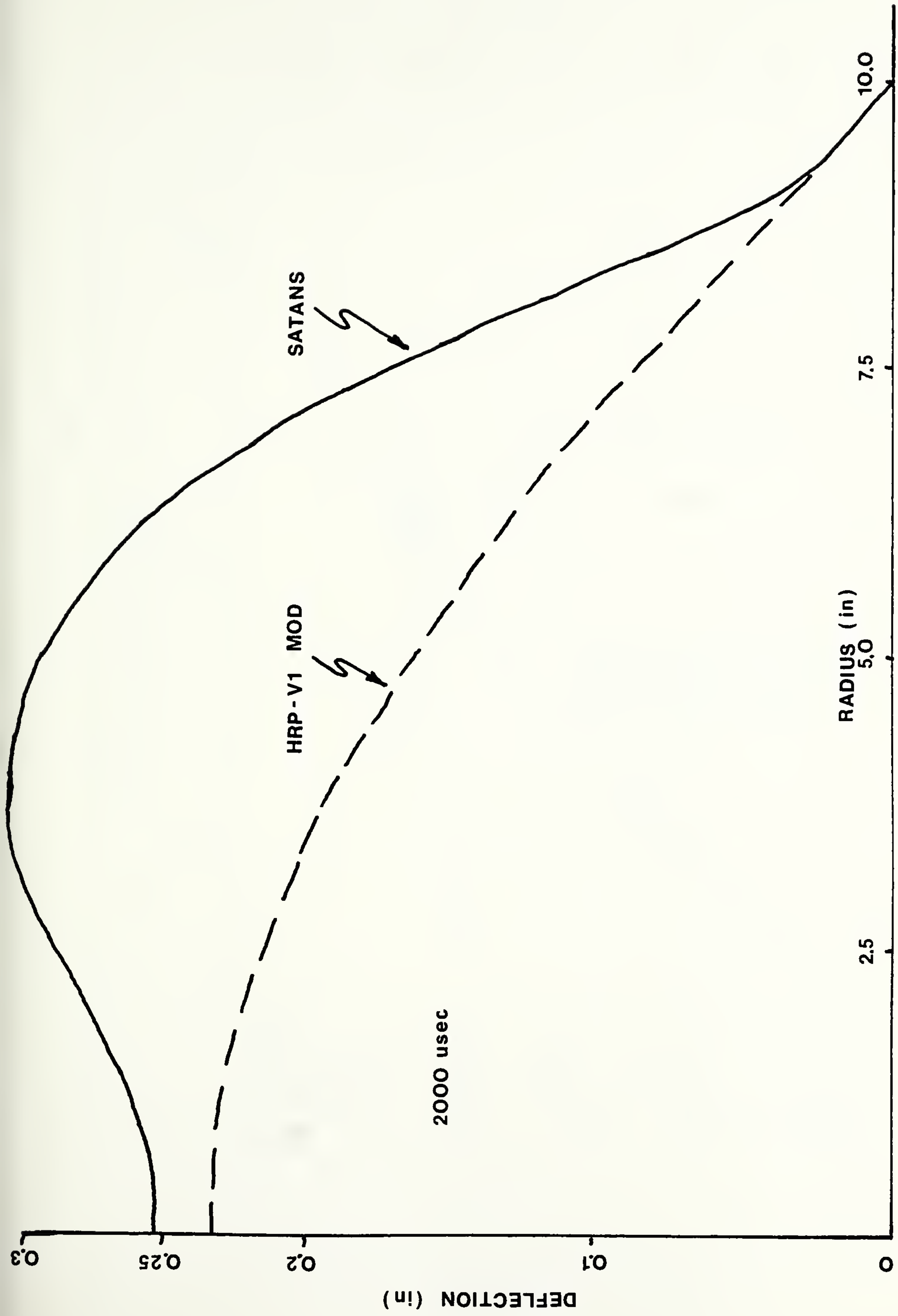

SATANS
HRP-V1 MOD
2000 usec
DEFLECTION (in)
0.3
0.25
0.2
0.1
0
2.5
5.0
7.5
10.0
RADIUS (in)

FIGURE 8

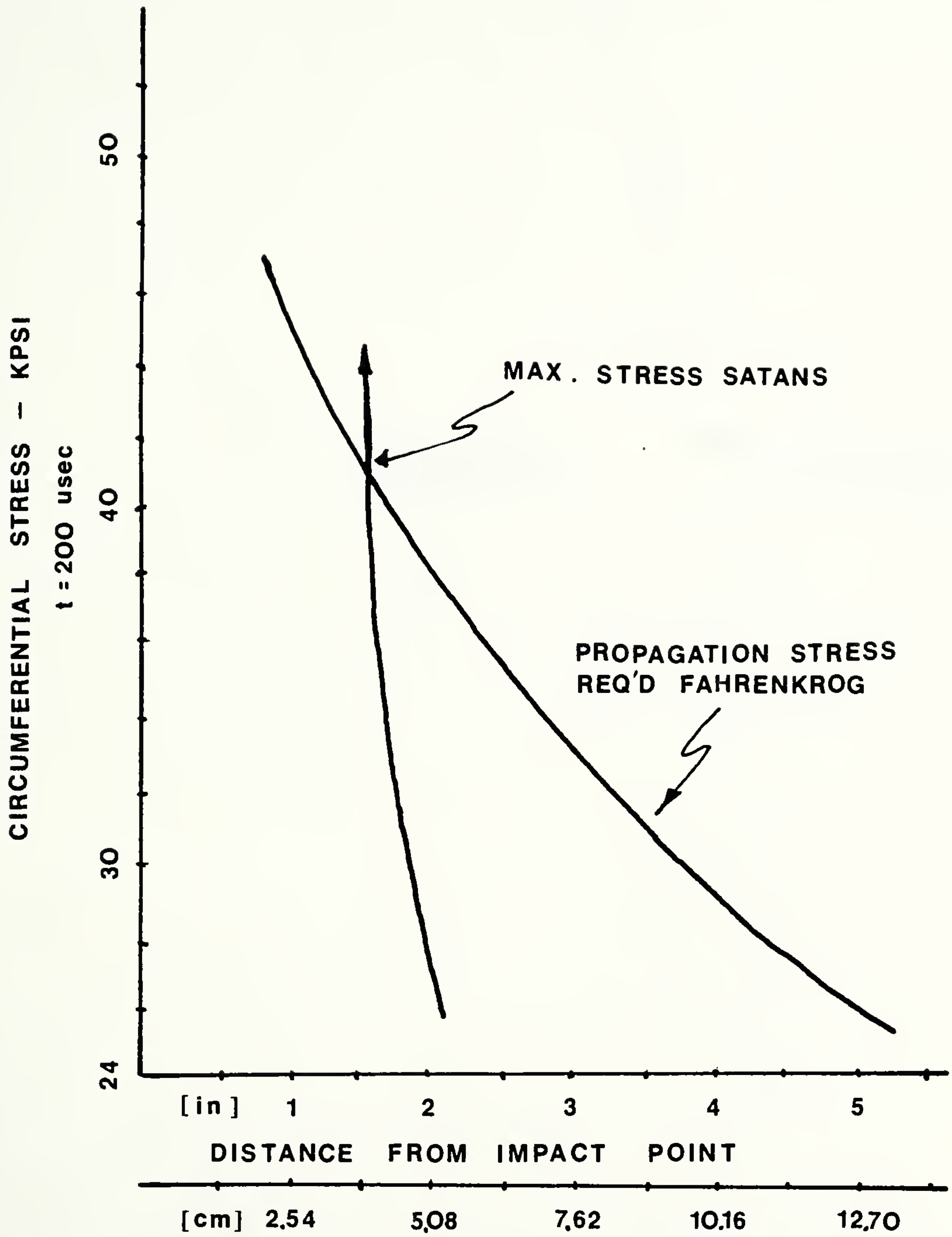
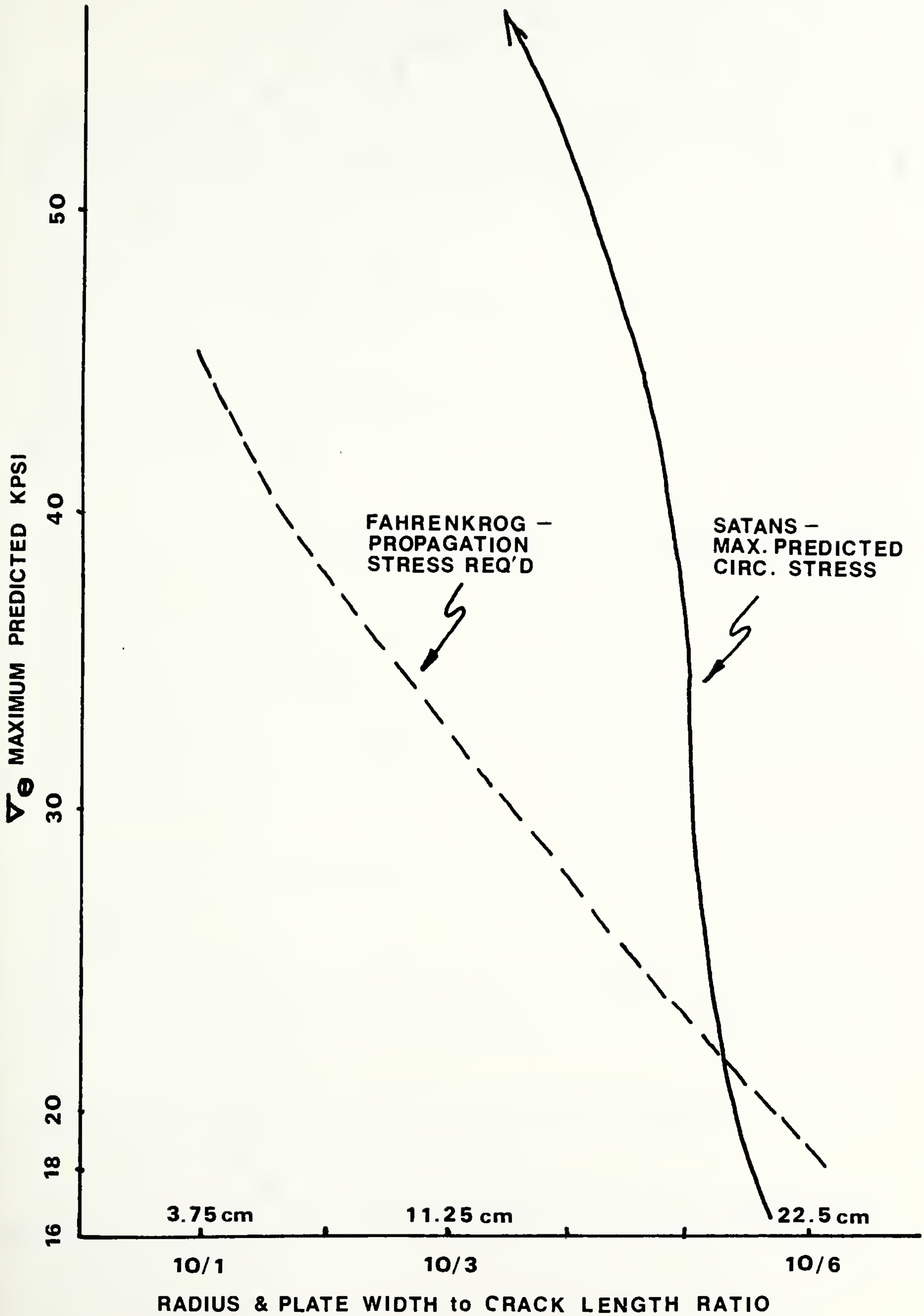

CIRCUMFERENTIAL STRESS - KPSI
t = 200 usec
50
40
30
24
MAX. STRESS SATANS
PROPAGATION STRESS
REQ'D FAHRENKROG
[in] 1 2 3 4 5
DISTANCE FROM IMPACT POINT
[cm] 2.54 5.08 7.62 10.16 12.70

FIGURE 9



σ_θ MAXIMUM PREDICTED KPSI
50
40
30
20
18
16
FAHRENKROG – PROPAGATION STRESS REQ'D
SATANS – MAX. PREDICTED CIRC. STRESS
3.75 cm
11.25 cm
22.5 cm
10/1
10/3
10/6
RADIUS & PLATE WIDTH to CRACK LENGTH RATIO

FIGURE 10

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